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Research Article

A Validation of the Ultrasound Wave Velocity Method to Predict Porosity of Dry and Saturated Cement Paste

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An approximate theoretical validation of the measured variation of ultrasound velocity with porosity of dry and saturated cement paste is proposed using finite element analysis of cement paste assuming as a multiphase composite. Cement paste is a multiphase composite consisting of solid cement and microscopic voids filled either with air or water. The void content in cement paste is directly related to strength and durability. Experimental tests showed that ultrasound wave velocity is decreased with the increase in porosity of cement paste, where pore sizes are similar in dimension to the wavelength of the sound enabling ultrasound to be used as a potential condition assessment technique. However, the variation of ultrasound wave velocity also depends on the fluid in the voids. Several finite element simulations using two commercially available software packages were performed for both fully saturated and dry blocks of cement paste with different porosities. Then back-calculated elastic moduli values from finite element simulations were used to compute the wave velocities of both fully saturated and dry cement paste with different porosities. The predicted ultrasound velocities with porosity for both dry and saturated cement paste are compared well with the laboratory measurements.

1. Introduction

Cement is counted among the key building materials both in the residential and nonresidential sectors. It was estimated that the global market was sized at around 395 billion U.S. dollars in 2016 [1]. Concrete is a cement-based building material which is critical worldwide, with over 500 million tons of annual production in the USA [2]. Unfortunately, various environmental factors affect cement-based materials, causing degradation, namely, aging, chemical and physical damage, freezing/thawing, fire, and corrosion of reinforcement [3, 4]. The durability and integrity of concrete are affected by cement paste because concrete is made of a matrix of cement mortar and aggregate. Hydrated and hardened cement paste is fluid-filled pores and an interconnected network of solid grains [5]. Hydrated cement paste properties such as strength, durability, shrinkage, and fracture behavior are affected by paste composition and structure [6]. It is well known that aggressive agents such as salt water will move through interconnected pores leading to degradation of concrete. Resistance to penetrating agents is widely recognized as an indicator of the durability of cementitious material [7]. Thus, cement paste porosity is a key structural property that needs to be quantified by performing in situ tests.

Currently, destructive and nondestructive in situ tests are used in estimating voids in concrete. Destructive tests require specimens to be removed from the structures to evaluate structural performance. This is not preferable as such tests may damage the structure. Nondestructive tests (NDT) and partial destructive tests, which do no damage or slightly damage the structure, are wildly used to evaluate the concrete performance. Nondestructive test using ultrasound is a common method to evaluate the performance of concrete structures.

Ultrasound techniques that detect defects, which measure the mechanical properties, or monitor the state of deterioration of concrete have been a topic of considerable interest to the civil infrastructure community [8, 9]. Nondestructive test using ultrasound is a common method to evaluate the performance of concrete structures, where the velocity of the ultrasound is the most widely used parameter for characterization. Low frequency (20–40 kHz) ultrasound is also used for leak detection [10] and for sediment decontamination [11].

Jones [12] proposed the use of ultrasound velocity measurements for nondestructive evaluation of Portland cement concrete. The ultrasound velocity method applies ultrasound to the test structure, and the wave propagates through the material and is received by the receiver. By analyzing the received signal, the condition of the material can be evaluated. The ultrasound pulse velocity is by far the most widely accepted method for assessing the quality of concrete in structures [13]. In addition, the frequency domain analysis can provide significant additional information [13, 14]. Elastic waves are directly related to the elastic properties of the porous material. Hence, ultrasound velocities can be used to estimate mechanical properties such as modulus of cement. When the ultrasound propagates in a homogeneous, linearly elastic material, the compression and shear wave velocity are related to the media's elastic moduli by the following expressions:

$$V_L = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}} = \sqrt{\frac{K+(4/3)G}{\rho}},$$
$$V_T = \sqrt{\frac{E}{2\rho(1+\nu)}} = \sqrt{\frac{G}{\rho}}, \tag{1}$$

where V_L is the compression wave velocity, V_T is the shear wave velocity, E is Young's modulus, ν is Poisson's ratio, and ρ is the density. These expressions clearly show the impact on ultrasound velocity of elastic properties of cement.

Since for porous material elastic moduli is a function of porosity [15, 16], ultrasound velocity in homogeneous material would depend on porosity. When an ultrasound wave propagates through a material, the wave velocity is related to its density and the elastic modulus [17] and the elastic tensor depends on porosity.

Over the last past decades, extensive research has being performed for the development of efficient and reliable methods to identify defects [18]. For instance, ultrasound velocity is the most common NDT method used for material characterization.

Cement paste forms the matrix phase of mortar and concrete; in order to fully understand the behavior of mortar and concrete, the first step would be to understand the performance of cement paste. Many researchers have investigated performance of cement paste by assuming the cement paste as a two-phase homogeneous nonporous paste with pores. Maalej et al. [19] used different water/cement ratios to create specimens with varying porosity values. Then broadband ultrasound spectroscopy [20] was used to induce ultrasound wave transmission into the materials with a single transducer. Ultrasound with 1 MHz frequency was applied to the sample. To transfer sufficient energy to the

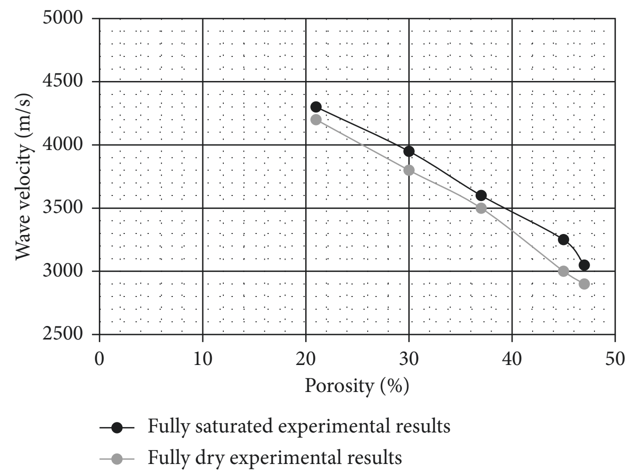

Figure 1: Experimental data of fully saturated and fully dry wave velocity with porosity [19].

sample, typically, adequate coupling should be applied. However, to avoid water penetration into the sample during the test, direct contact was chosen instead of immersion coupling. The single transducer was used as both transmitter and receiver. The time to receive two signals $s1(t)$ which is the signal reflected from the top of the sample and $s2(t)$ which is the signal reflected from the bottom of the sample was read. Then, pulse velocity was obtained using the following equation:

$$V_L = \frac{2e}{\Delta t}, \tag{2}$$

where e is the thickness of the sample and Δt is the time delay between signals $s1(t)$ and $s2(t)$. Experimental tests showed that the ultrasound wave velocity of saturated concrete of given porosity is higher than that of dry concrete. The results also show that the contribution of moisture saturation on the ultrasound wave velocity was significant. Maalej [21] prepared five samples with varying cement to water ratios 0. To achieve workability of the cement paste, 1% of superplasticizer adjuvant was added to the cement by weight. During the first 48 hours, the samples were kept in the watertight environment. Then, the samples were stored in a $Ca(OH)_2$ solution at constant temperature for another 28 days. The samples stored in the lime solution were considered fully saturated. For dry samples, they were oven dried at 60°C. Samples were taken out for test when they had constant weight. Maalej et al. [19] showed that the ultrasound wave velocity decreased with the increase in porosity of cement paste (Figure 1).

Maalej et al. [19] also compared the above experiment results to predictions from four theoretical micromechanical models. All micromechanical models could not accurately predict the experimented results especially when the voids were filled with air or water. Because of this, this research attempts to provide an approximate theoretical basis for the measured variation of ultrasound velocity with porosity of dry and saturated cement paste using the finite element method (FEM).

Table 1: Cement paste elastic moduli at zero porosity [19].

	Cement paste at zero porosity		Pores	
	Bulk (MPa)	Shear (MPa)	Bulk (MPa)	Shear (MPa)
Dry	30,182	17,662	0	0
Saturated	33,919	17,884	2,200	0

Table 2: Densities of dry and saturated phases [19].

	Dry (kg/m^3)	Saturated (kg/m^3)
Cement paste at zero porosity	2,579	2,579
Pores	1.204	1,000

2. Finite Element Method Model Setup

The finite element method (FEM) is a numerical method for predicting how an object reacts to real-world forces and energy. It does not yield an exact solution but rather an approximation to the exact solution. Since the late 1960s, the finite element method has been used for a wide range of engineering problems. By using the FEM, the continuous physical problem can be solved to calculate the discretized nodal values. The FEM has been known to accurately calculate the elastic properties of objects [22] and was successful in estimating the elastic moduli of composite materials [23, 24]. In this research, two commercially available software packages were used to simulate the elastic behavior of cement paste, where the elastic modulus of cement paste with different porosities was back-calculated. Ultrasound testing in concrete is mainly used to evaluate the performance of the material under compressive loads [25]. Hence, in this research, model simulations were performed subjected to compressive loads.

2.1. Simulation of the Model Geometry. Like most of the micromechanics models, cement paste was treated as two-phase composite including nonporous cement and voids. Consequently, a solid cement block was proposed, and voids in the cement were idealized and concentrated together as inclusions inside solids. By adjusting the volume of inclusions, different porosity values of cement were simulated. Also by adjusting the material inside inclusions, dry and fully saturated situations were performed. Before the geometry is scoped, the material properties should be input to the program.

2.2. Void Shape. In micromechanical models, inclusion shape is usually ignored such as in bounding methods of Hashin [26], Hashin and Shtrikman [27], and Walpole [28] or by using specific shapes. It is convenient to have symmetrical inclusions such as ellipsoids, spheres, elliptical cylinders, circular cylinders, and penny- or needle-shaped ellipsoids. Consequently, symmetrical inclusions were used in this research. The orientation at the center of the cement block was related to the global coordinate system and symmetrically distributed inside the cement block.

2.3. Element Types and Boundary Condition. A 3D SOLID element was used to simulate the nonporous cement paste. A 3D and 8-node linear element with three degrees of freedom for each node-translation in the X, Y, and Z directions was used. A hydrostatic fluid element (HSFLD242) was used to simulate the fluid inclusion such as void filled with fluids inside a solid model in order to modeling fluid-solid interaction with incompressible or compressible fluids under uniform pressure. It can be used in geometrically linear as well as nonlinear static and transient dynamic analyses [29]. When applying a vertical stress as a surface load on the top element face, it will be supported by the bottom face of the block; hence, there is no vertical displacement and zero rotation of the bottom surface. The remaining four sides will be free boundaries.

3. FEM Simulation

Two different commercially available FEM software packages were used in this research, where the second software package was used to compare and validate simulation results of porous cement paste filled with fluid.

3.1. FEM Simulations. For any FEM simulations, representative material properties are needed. The same material properties reported in Maalej et al. [19] were used since this study attempts to compare numerical simulations with experimental results. Their detailed experimental results of Maalej et al. [19] were presented in [30]. Soltani [30] obtained values of bulk and shear moduli for the cement paste at zero porosity from ultrasound velocity measurements and unit weight by using (1), and numerical values are listed in Table 1. The density of pore fluids used in this simulation and the dense cement paste with no porosity are listed in Table 2. The reported Young's modulus and Poisson's ratio of zero porosity cement paste were 44,337 MPa (9.26e8 psf) and 0.28, respectively, which correspond to a wave velocity of 4688 m/sec (15381 ft/sec) [19].

3.2. Back-Calculated Elastic Modulus. After performing the FEM simulations, the elastic modulus was back-calculated using the following equation:

$$E = \frac{F * L_0}{A_0 * \Delta L}, \quad (3)$$

where E is Young's modulus, F is the force exerted on an object under compression, here 0.34 MPa (7200 psf) was used, A_0 is the actual cross-sectional area through which the force is applied, ΔL is the amount by which the length of the object changes, and L_0 is the original length of the object. After performing the FEM simulations, the elastic modulus was back-calculated by using (3). Please note that with an

TABLE 3: Summarization of back-calculated Young's modulus and associated errors for different inclusion shapes.

Inclusion shape	Porosity	Young's modulus from ANSYS	Error
Sphere	5%	39,166 MPa	
Circular cylinder	5%	38,399 MPa	2%
Ellipsoid with axial ratio of 1.3	5%	40,267 MPa	3%

TABLE 4: Summarization of back-calculated Young's modulus and associated errors for different numbers and distributions of spheres.

Numbers and distribution	1 single sphere	2 spheres, random	2 spheres, vertical	2 spheres, horizontal	4 spheres, square	4 spheres, star
Young's modulus (MPa)	37,059	36,819	38,112	35,718	37,969	37,115
Error		1%	3%	4%	2%	0%
Numbers and distribution	8 spheres, vertical	8 spheres, horizontal	9 spheres	10 spheres, horizontal	10 spheres, vertical	10 spheres, varied sizes
Young's modulus (MPa)	38,830	37,825	37,011	38,017	37,825	36,820
Error	5%	2%	0%	3%	2%	1%

inclusion or a void, the back-calculated Young's modulus would be lower than that of cement without voids.

3.3. Shape of Inclusions. As mentioned before, modeling geometry inclusions such as ellipsoids, spheres, elliptical cylinders, circular cylinders, or penny- or needle-shaped ellipsoids are often used in micromechanical models. Ellipsoidal inclusions can be characterized by the aspect ratio, which is the vertical axis over horizontal axis.

Maalej [21] showed five different aspect ratios:

$\alpha = 1$ spherical inclusion

$\alpha > 1$ prolate spheroid (needle-shaped inclusion)

$\alpha < 1$ oblate spheroid (penny-shaped inclusion)

$\alpha = 0$ flat disk

$\alpha = \infty$ cylinder

The objective of this research was to compare the estimated wave velocity using simulation with the experimental data. In this research, circular cylinders and spheres were chosen as inclusions in the model. Since the cement paste is being considered as a two-phase material, voids distributed in the paste were represented a single equivalent inclusion or void at the center of the block. The size of the inclusion was adjusted to represent different void ratios of the paste. Then with different inclusion sizes, simulations were repeated with the same assigned material mesh and boundary conditions. Using the average displacements from simulation Young's modulus was calculated. For a certain porosity, different void shapes like sphere and circular cylinders can be calculated. With the same porosity of 5%, Young's modulus of the model with the sphere shape inclusion was 39,116 MPa (8.18e8 psf), that for the model with the ellipsoid shape inclusion was 40,267 MPa (8.41e8 psf), and that for the model with circular cylinders was 38,399 MPa (8.02e8 psf), with a maximum error of 5% with respect to spherical inclusion. Test results are listed in Table 3. Based on simulation results, the shape of the inclusion had minimal impact on the back-calculated Young's modulus, so spherical voids were used in remaining simulations.

3.4. Number of Inclusions and Their Distribution. In the FEM simulation, an equivalent inclusion was used to represent the voids in the cement paste where voids in the cement paste are randomly distributed. Thus, it is necessary to evaluate the impact of the above assumption. Hence several simulations of block with inclusions distributed throughout the block were performed for given porosity, and the error between back-calculated modulus of single inclusion with inclusions distributed throughout the block was found to be insignificant. For a given porosity value of 10% several inclusions with varying distributions were simulated. Table 4 compares impact of number of equivalent inclusions and their distribution for a given void ratio showing a maximum error of 5%.

3.5. Variation of Porosity. By adjusting the size of the sphere, the model can simulate different porosity values. Five different porosity values were simulated in this research. By using a given porosity value, the total volume of the void can be calculated, and therefore, the radius of sphere is calculated based on that volume. The simulation results and the back-calculated computed Young's modulus values presented in Figure 2 show that Young's modulus decreases with the increase of porosity.

3.6. Dry and Fully Saturated Inclusions. To test the changes in ultrasound velocity in dry or moisture-saturated cement paste, different fluid elements were assigned to the equivalent sphere in the FEM model to simulate air- and water-filled voids. This was the most challenging aspect of this research, where the incorporation of fluid filled voids into elastic analysis without elastic modulus value for the fluid. For this purpose, the first FEM package represented the fully enclosed fluid using a special element called HSFLD242, and

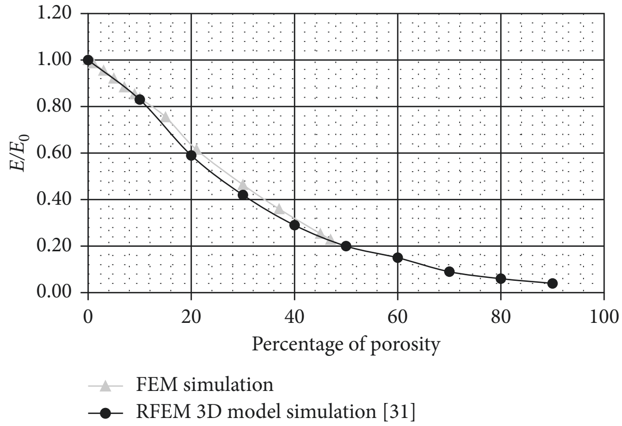

Figure 2: The variation of Young's modulus ratio with porosity.

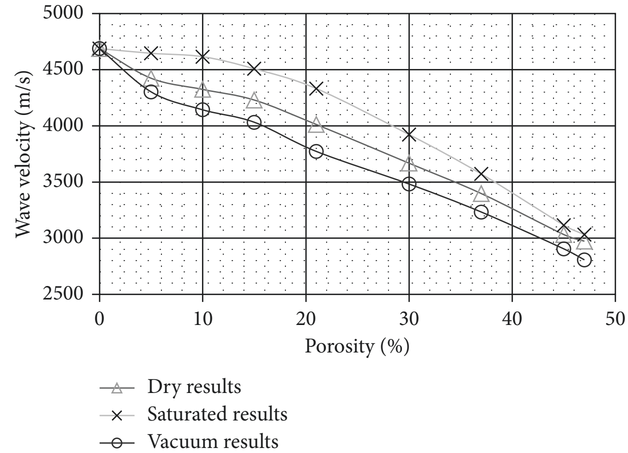

Figure 3: Variation of wave velocity with porosity based on fully saturated, fully dry, and vacuum results.

the second FEM package represented the same using the concept called fluid cavity. When voids are filled with different fluids, the bulk modulus of the fluid would considerably impact the compressibility of the voids.

3.7. Simulation Results. In this research, it was attempted to simulate the porosity values reported in Maalej et al. [19] specifically 21%, 30%, 40%, and 45%. The void volume corresponding to above porosity values for one cubic foot volume was first computed. Then based on the above void volumes, radius of inclusion of the sphere at the center of the block was computed. After that, applying the zero-void elastic modulus of the cement paste was assigned to the block, and the material of the inclusion defined as air. The same process was used to generate mesh, and the previously defined boundary conditions were applied. By applying the vertical pressure on the top surface of the block, the enclosed fluid will expand and increase in fluid pressure inside the void. Consequently, the correct fluid pressure should be applied to the model. However, it is difficult to obtain a deformation versus pressure relationship for the inclusion. Please note that air is compressible and water is incompressible. As a result, the pressure inside the inclusion was assumed as equal to 1 standard atmosphere and the applied pressure of 0.34 MPa (7200 psf), respectively, to air and water inclusion. First, the fluid element was assigned as air to simulate the dry condition. The initial pressure of the air in the sphere is one atmosphere, and after the boundary conditions were applied, the pressure inside the inclusion was assumed as one atmosphere. Then, the average displacement in y-axis was used to compute Young's modulus by using (3). However, to back-calculate the wave velocity, Poisson's ratio should be determined. Accordingly, the average lateral displacement values were used to calculate Poisson's ratio and the modified density based on the porosity. Finally, Equation (1) was used to obtain the longitude wave velocity. Then the radius was changed to simulate the different porosity values, and the above procedure was repeated. To simulate the fully saturated situation, a fluid element was used instead of air, and the above was repeated. But the pressure inside the inclusion is increased to applied pressure of 0.34 MPa (7200 psf). The FEM vacuum simulation which was reported in Figure 2 was extended and used to compare with the dry and saturated cement paste results. Figure 3 shows the simulation results.

4. Discussion of Results

The impact of the compressibility of the material in the inclusion for a given porosity, in vacuum, produced the lowest wave velocity followed by the dry void filled with air and then the void filled with incompressible water was shown in Figure 3. For example, when porosity value is equal to 21%, wave velocities are 3775 m/sec (12385 ft/sec) for a vacuum inclusion with no compressibility of the inclusion, 4000 m/sec (13123 ft/sec) for an inclusion filled with partially compressible air, and 4325 m/sec (14190 ft/sec) for an incompressible inclusion filled with water. Compare those to a value of 4688 m/sec (15380 ft/sec) for no inclusion. The results are listed in Tables 5 and 6.

The FEM simulation results show that the ultrasound velocity will decrease when the cement paste porosity is increased no matter whether it is dry or saturated. As mentioned before, ultrasound testing in concrete is mainly used to evaluate the quality of the material based on its porosity. Typically, larger porosity produces weaker cement. With higher porosity of concrete, aggressive fluids can enter concrete and leaching of calcium can occur, forming weaker material such as gypsum. Also, voids filled with fluid have much lower elastic modulus. The FEM simulation result also shows that, under the same applied vertical stress, there is higher deformation of the block with higher porosity, proving that the material becomes weaker when the porosity increases. From the simulation result, the ultrasound velocity will decrease with the increase in porosity because higher porosity means lower elastic modulus. Thus, the ultrasound method is a potentially powerful tool for the condition assessment of concrete. With degradation, the porosity is increased, causing the material to become weaker. On that account, ultrasound velocity via elastic modulus and the porosity can be used to estimate the condition state of structures. Maalej et al. [19]

Table 5: Results for simulating different porosities under fully dry situation.

		Fully dry		
Porosity (%)	Young's modulus, E (MPa)	Poisson's ratio	Density, ρ (kg/m^3)	Velocity (m/s)
5	41,998	0.22	2450	4424
10	38,020	0.22	2321	4324
15	34,356	0.22	2192	4230
21	28,739	0.22	2038	4013
30	21,276	0.22	1806	3668
37	16,433	0.22	1625	3398
45	11,431	0.22	1419	3033
47	10,590	0.22	1367	2973

Table 6: Results for simulating different porosities under fully saturated situation.

		Fully saturated		
Porosity (%)	Young's modulus, E (MPa)	Poisson's ratio	Density, ρ (kg/m^3)	Velocity (m/s)
5	42,213	0.28	2500	4646
10	40,349	0.28	2421	4616
15	37,236	0.28	2342	4508
21	32,997	0.28	2247	4332
30	25,340	0.28	2105	3923
37	19,913	0.28	1995	3572
45	14,193	0.28	1868	3116
47	13,214	0.28	1837	3033

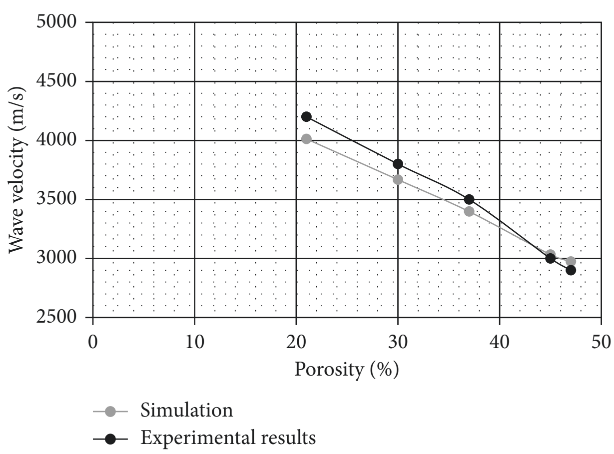

Figure 4: Comparison of back-calculated wave velocity of fully dry cement paste with those measured (experimental results of Maalej et al. [19]).

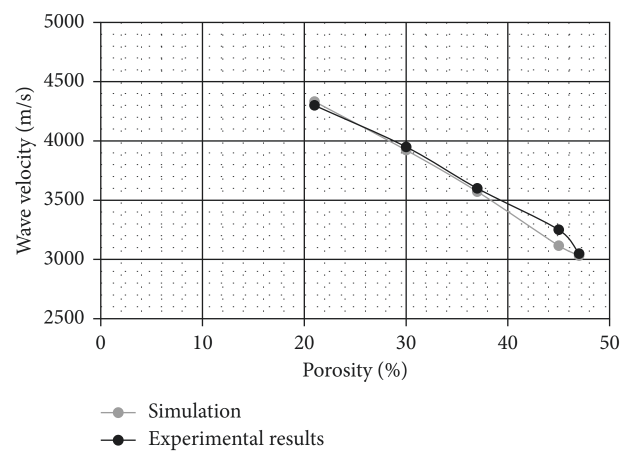

Figure 5: Comparison of back-calculated wave velocity of fully saturated cement paste with those measured (experimental results of Maalej et al. [19]).

showed that the ultrasound wave velocity decreased with the increase in porosity of cement paste. However, there is no theoretical basis for the measured variation of ultrasound velocity with porosity of dry and saturated cement paste.

This study attempted to provide a theoretical explanation for the variation of ultrasound wave velocity with porosity for both dry and saturated cement paste using FEM simulations. In FEM simulations, the fluid is defined by the hydrostatic fluid element, which needs the bulk modulus of fluid. The bulk elastic properties of a material determine its elastic deformation and hence the wave propagation. With different bulk moduli, the compressibility values of the air and water voids are different. As a consequence, the deformation of void filled with air or water will be quite different. Cement paste filled with a water void is much harder to compress due to the higher bulk modulus of water, when compared with that of a void filled with air. Ultrasound testing of concrete is mainly used to evaluate the quality of the material, via its compressibility. Ergo, voids filled with different fluids will have different moduli due to the different enclosed fluids. As a result, the wave velocity of saturated cement paste is faster than that of dry cement paste at the same porosity due to the lower compressibility of water in the voids. This causes the elastic modulus of saturated cement paste to be higher than that of dry cement paste for the same porosity. Back-calculated, the wave velocity of saturated cement paste is faster than that of dry cement paste, as shown in Figures 4 and 5 that show comparison of measured results from Maalej et al. [19]

and simulation results from this research confirming a good comparison. Figures 4 and 5 also provide a theoretical basis to validate the experimental results of Maalej et al. [19].

5. Summary and Conclusions

Nondestructive test using ultrasound is a common method to evaluate the performance of concrete structures, where the velocity of the ultrasound is the most wildly used parameter for characterization. Experimental tests show that the ultrasound wave velocity is decreased with the increase in porosity of cement paste. Hence ultrasound can be used as a potential condition assessment technique and also can be used to characterize the micromechanical structure. However, voids are filled with water and air provided separate ultrasound wave velocity variations. The FEM simulations using two commercially available software packages to provide an approximate theoretical validation of above experimental results were performed. The FEM simulation showed that void shape, number of void, and distribution of void do not have a major impact, and hence, the porous cement paste was idealized and simulated as one equivalent void at the center of a cube. The FEM simulation showed that under the fully saturated conditions the wave velocity is little faster than that under dry conditions. By comparing the simulated and back-calculated wave velocities with those measured for different porosities, this study attempted to provide a theoretical basis variation of ultrasound wave velocity with porosity for both dry and saturated cement paste. The simulated and back-calculated wave velocity values compared well with the laboratory measurements, confirming that the ultrasound velocity of dry and saturated cement paste is a function of elastic properties of cement, porosity, and compressibility of the voids.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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